A New Method for Quantifying Forest Inventory Mortality

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Tree mortality has typically been assessed in forest inventories through summaries of mortality by location, species, and causal agents. Although these methods have historically constituted the majority of forest mortality analyses, they are inadequate for robust assessment of mortality trends and dynamics. In order to afford a new method of analyzing tree mortality in forest inventories, survival analysis techniques were used to estimate survival and hazard functions for FIA periodic inventories in Minnesota. The study's methodology for applying survival analysis techniques to FIA inventories successfully estimates survivor and hazard functions. Classifying individual trees into classes of DBH and DBH growth may facilitate application of survival analysis techniques to forest inventories by providing a surrogate for tree ages and vigor. Applying survival analysis techniques to forest inventories may provide forest inventory analysts with the ability to test tree mortality hypotheses, summarize regional tree mortality trends, and afford a solid foundation for development of individual tree mortality models.

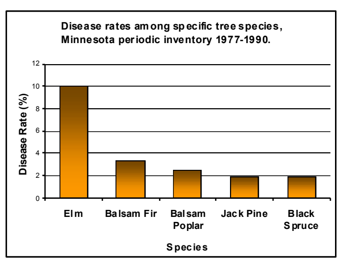
Current Methodologies

Past pest/disease epidemics
(*Dutch Elm Disease, Gypsy Moth, and Chestnut Blight*)

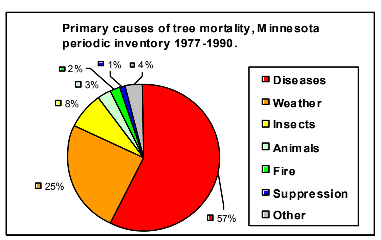
Sudden Oak Death

Emerald Ash Borer

Possible future epidemics



(from Leatherberry et al 1990)



(from Leatherberry et al 1990)

The majority of current forest mortality analyses include simple summarizations of tree mortality rates among species groups and causes of tree death. More sophisticated analyses include individual tree logistic models which may not be applicable for large-scale inventory analysis.

Given the past diseases and epidemics that have greatly altered our North American forest ecosystems and the threats of future forest health hazards, novel and statistically robust techniques for assessing forest mortality would greatly benefit forest inventory analysts.

Survival Analysis and Forest Mortality

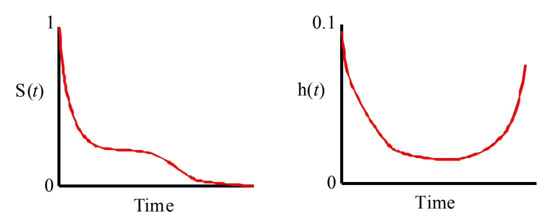
Survival analysis is:

- Class of statistical methods for studying the occurrence and timing of events (death)
- Commonly applied in medical sciences
- Data used: age, time, death, covariates

Central Functions of Survival Analysis: The Survivor (cumulative risk of mortality) and Hazard Functions (time interval risk of mortality)

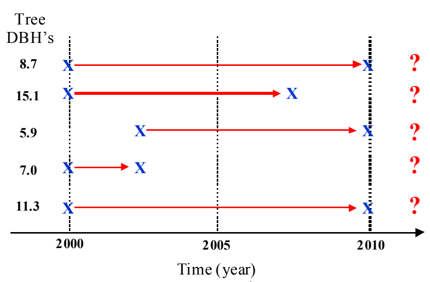
$$S(t) = \Pr\{T > t\} = 1 - F(t)$$

$$h(t) = \lim_{\Delta t \to 0} \frac{\Pr\{t \le T < t + \Delta t \mid T \ge t\}}{\Delta t}$$



Survivor Function

Hazard Function



Forest Survival Analysis Supposition

For forest inventories that remeasure trees at regular intervals, DBH and ΔDBH (time two DBH - time one DBH) may assign individual trees to cells within a matrix of tree size and vigor. The survivor function *S(t)* is defined at a time *t* as the chance that the time to the event is greater than or equal to *t*. In this study, the "clock" starts at the first forest inventory, when a tree begins to be "at risk" for the event or begins to be monitored for the event. Stating this in terms of DBH, the clock is ΔDBH (the increase in DBH from initial survey). Our survival function *S(ΔDBH)* gives the chance that a tree will die after it has grown by at least ΔDBH = k cm. For example, *S(4 cm)* estimates the proportion of the population of trees that will survive to increase their DBH by 4 cm. The hazard function *h(t)* gives the chance of an event occurring at time *t* given that the subject has survived up to *t*. In terms of DBH, *h(ΔDBH)* gives the chance that a tree that has survived and grown k cm will die at that point. The individual tree variables of DBH and ΔDBH may allow application of survival analysis to forest inventories thereby providing a novel method of assessing forest mortality dynamics.

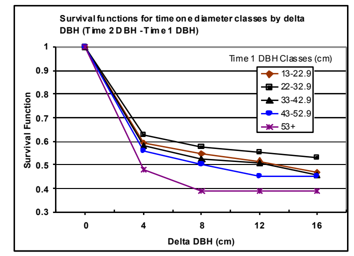
Survival Analysis Surrogates:

Age → Tree DBH
Tree Vigor → DBH Growth

Study Methods

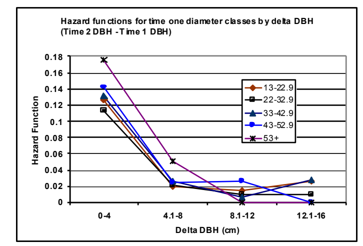
- Data: Minnesota 1977-1990
- Variables: DBH 1, DBH 2, TOTBA, DAM1, DAM2, BAL, CC, and CR
- Determine Functions
  - –Survival: *S(ΔDBH = k cm)*
  - –Hazard: *h(ΔDBH = k cm)*
- SAS → PROC LIFETEST

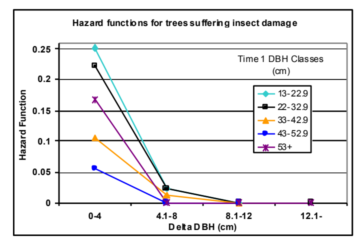
New Mortality Analysis Output



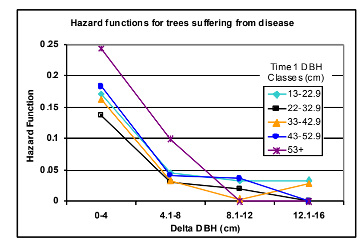
The survivor function estimates the cumulative distribution of mortality across a sample of trees classified by size and growth rate. Any atypical mortality would be readily observed utilizing this methodology

The hazard function estimates the probability of mortality occurring for trees by DBH class and growth rate.





Insect Damage



Disease Damage

Separate hazard functions for insect and disease damaged inventory trees indicate differences in dynamics of tree mortality between the two damage agents

Results: Log-rank test for effects of covariates on survivor functions by species and DBH class, Minnesota 1977-1990

Species	Variable	DBH Classes 13.0-22.9	23.0-32.9	33.0-42.9	43.0-52.9	53.0+
Red and Jack Pine	CRAT	X	X	X		
	CC	X				
	TOTBA		X	X	X	
	BAL	X		X		
Black Spruce/Fir	CRAT	X	X	X		
	CC		X			
	TOTBA	X	X			
	BAL	X	X			
Maples	CRAT	X	X	X	X	X
	CC	X	X	X	X	X
	TOTBA		X			
	BAL			X		
Paper Birch	CRAT	X	X	X		
	CC	X	X	X	X	
	TOTBA					
	BAL	X				
American Elm	CRAT	X	X			
	CC	X	X	X	X	
	TOTBA	X			X	X
	BAL	X		X		

(X → p-value < 0.05)

Beyond graphical display of the survivor and hazard functions, log-rank tests for effects of covariates and tests of equality among strata may allow for testing of mortality hypotheses.

Forest inventory analysis has traditionally been geared toward simple summarizations at the landscape-scale and focused on logistic regression modeling at the individual tree-scale. Few advances or technologies have been forwarded for robust analysis of forest mortality dynamics at the landscape-scale. This study proposed a new approach to forest mortality assessment through combination of established survival modeling techniques (survivor/hazard functions) with traditional quantifications of forest stand attributes (DBH distribution/diameter growth). Although this technique suggests a paradigm shift in forest mortality analyses and non-standard application of survival analysis techniques, a new forest mortality analysis approach may be gained that provides statistically defensible assessments of tree mortality across forest types, locations, and varying damage agents.